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Tree-ring reconstruction of past lahar activity at Popocatépetl volcano, Mexico

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Abstract: Lahars represent a major threat on the slopes of volcanoes all over the world. In order to realistically assess hazards, knowledge on the occurrence and timing of past lahar activity is of crucial importance. However, archival data on past events is usually scarce or completely missing. Tree-ring records have repeatedly proved to be a reliable data source for the reconstruction of past geomorphic events. However, tree rings have seldom been applied for the identification of past lahars. Therefore, it was the aim of this study: (i) to identify and describe disturbances in tree growth induced by well-documented lahar events and on this basis; and (ii) to recognise older, unknown lahar events with tree-ring analyses. Based on these goals, we collected 140 tree-ring series from 62 trees (*Abies religiosa, Pinus hartwegii* and *Pinus ayacahuite*) standing inside or adjacent to the lahar channel in the Huiloac gorge at Popocatépetl volcano, central Mexico. Most commonly, the known lahar events of 1997 and 2001 resulted in abrupt changes in tree-ring width as well as injuries. The same growth disturbances could be identified in the tree-ring series, indicating that five previously unknown lahar events would have occurred during the 20th century. Popocatépetl is one of the best surveyed volcanoes in the world and past eruptions are precisely noted in archives. As most of these unknown events occurred during periods with no volcanic activity, we believe that they were rainfall-induced rather than related to volcanic activity. In order to assess rainfall intensity threshold values for the triggering of events, the analyses of meteorological data needs to be integrated. In general, the investigated tree species proved to be highly suitable for the reconstruction of mass-movement processes. Therefore, the applied methods can be transferred to other locations where data on past events are missing.

Key words: Tree rings, lahar, dendrogeomorphology, *Abies religiosa, Pinus hartwegii, Pinus ayacahuite*.

Introduction

Lahars are rapid, saturated flows of water and rock fragments that occur on volcanoes (Smith and Fritz, 1989). This definition takes into account two classic geomorphic processes, debris flow and hyperconcentrated flow, and links them specifically to volcanic environments (Thouret and Lavigne, 2000). Lahars can be triggered in relation to volcanic activity (syn-eruptive) when an eruption causes heavy melting of snow or glaciers on the flanks of volcanoes. Lahars may also occur in periods of volcanic inactivity (post-eruptive or unrelated to eruptions) through heavy rainfall on unconsolidated volcanic deposits (Vallance, 2000). Due to their unpredictable occurrence, high sediment content that includes large boulders, and ability to rapidly travel long distances over low gradients, lahars represent one of the most destructive of natural hazards (Fisher and Schmincke, 1984; Vallance, 2000).

Active volcanoes and related lahars have repeatedly caused damage and loss of live over the past decades, for instance at Nevado de Ruiz volcano (Colombia) in 1985 (Pierson *et al.*, 1990), Colima volcano (Mexico) in 2000 (Davila *et al.*, 2007), at Ruapehu volcano (New Zealand) in 1953 (Cronin *et al.*, 1997) and Casita Volcano (Nicaragua) in 1998 (Scott *et al.*, 2005). Even though much research has been undertaken to

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improve the understanding of the mechanisms of lahar triggering and occurrence, data on past activity generally remains scarce. In order to fully understand and mitigate hazards posed by lahars, it is very important to improve our knowledge of previous events.

An approach for the reconstruction of past mass-movement activity is tree-ring analysis, as it has proved to be a very reliable tool for the dating and understanding of surface processes and their dynamics. In volcanic research, tree rings have mainly been used for the reconstruction of past eruptions and related short-term climate changes (LaMarche and Hirschboek, 1984; Scuderi, 1990; Briffa *et al.*, 1998; Biondi *et al.*, 2003; Sheppard *et al.*, 2008). Volcanic deposits have generally been dated through an assessment of the death moment of overridden trees (Brantley *et al.*, 1986; Yamaguchi *et al.*, 1990; Salzer and Hughes, 2007). Yamaguchi and Hoblitt (1995) combined the dating of overridden trees with a minimum age dating of deposits, in order to improve understanding of the chronology of events. Cameron and Pringle (1986) used tree rings to date a lahar event at Mt St Helens. Similarly, Solomina *et al.* (2008) dated pyroclastic flows that occurred in the 18th century by analysing tree rings of buried stumps. Even though these studies resulted in new insights on the timing of single events, they failed to provide longer and more complete chronologies of past activity. Tree-ring dating methods have not previously been applied to living trees in order to reveal the frequency and occurrence of past lahar events.

In contrast, tree-ring reconstructions have been used extensively for assessment of the timing, frequency and spatial activity of debris flows on cones (Hupp, 1984; Strunk, 1989, 1991, 1997; Stoffel and Beniston, 2006; Bollschweiler *et al.*, 2007, 2008a; Stoffel *et al.*, 2008). As debris flows represent a geomorphic process with largely similar flow behaviour as lahars – with the difference that they are not related to volcanic environments – trees might react in a comparable way to the impact of both processes.

Therefore, it is the aim of this study to apply tree-ring dating techniques well known for the study of other geomorphic processes to the reconstruction of past lahar activity. We first identified growth changes in different conifer tree species influenced by the lahar events of July 1997 and January 2001 on the slopes of Popocatépetl volcano, Mexico. A total of 62 *Abies religiosa*, *Pinus hartwegii* and *Pinus ayacahuite* trees were sampled in the Huiloac gorge, which were obviously influenced by these events. We then sought to reconstruct older unknown lahar events in the Huiloac gorge, based on growth disturbances in the tree-ring series.

Regional setting

Popocatépetl volcano (19º1'N, 98º37' W, 5450 m asl) is located 70 km southeast of Mexico City and 50 km west of the city of Puebla, in the central area of the Trans-Mexican Neovolcanic Belt, a region of active volcanoes that extends 1200 km across Mexico. Popocatépetl is a stratovolcano that originated in the early Pleistocene, and is the result of the overlapping of 5 successive volcanic edifices. The genesis of the present volcanic edifice dates back 23 000 years to the last great destructive period (Robin and Boudal, 1987). The last major eruptive period occurred in the 9th century and was characterised by recurrent Plinian explosions. At the same time, massive lahars were triggered and travelled dozens of kilometres beyond the volcano, destroying several large settlements in the vicinity (Siebe *et al.*, 1996). Historical records confirm that, after this period, volcanic eruptions occurred during the 14th, 16th and 18th centuries (Macias, 2005), but there are no accounts of lahar activity. Popocatépetl was virtually inactive during the 19th century, with only intermittent fumarolic activity. A short eruptive phase began in late AD 1919, reaching maximum activity by early 1921 (Camacho, 1925), but the volcano then returned to total inactivity in 1927 (Ward, 1985).

References dating as far back as the Spanish conquest refer to a large glacier on the north face of Popocatépetl's summit cone. By the mid-19th century, the glacier extended as far as 4150 m asl, but during the eruptive period 1920–1927, it receded considerably (Priester, 1927; White, 1981) and disappeared completely in 2003 (Andrés *et al.*, 2007). At its maximum extension during the Little Ice Age, the glacier had three tongues, and as the ice receded, erosion formed three proglacial gorges. The three gorges converge at Huiloac gorge, which is channeled downstream in a ENE direction (Figure 1) (Palacios *et al.*, 2001). The gorge channel of Huiloac is 20–60 m deep and 15–20 m wide, and incises dark grey sediments derived from ashfalls dating to historical episodes and pumice fall materials that alternate with laharic and pyroclastic flow deposits from the 9th century and earlier (Macias, 2005). Huiloac gorge runs through the towns of Santiago de Xalitzintla and San Nicolas de los Ranchos, located at elevations of 2560 and 2440 m, respectively, before terminating in an alluvial fan 25 km from the crater.

Prior to the start of volcanic activity at Popocatépetl in December 1994, debris flows triggered by tropical rains occurred in Huiloac gorge in September 1993. The flows caused considerable damage to the town of Santiago de Xalitzintla (Muñoz-Salinas, 2007). Several volcanic explosions took place during the period 30 June–1 July 1997, which eroded and grooved the glacier surface (CENAPRED, 2009). On 1 July 1997, the glacier meltwater and heavy rains triggered the largest lahar to take place at Popocatépetl during the present eruptive phase. Sediments from the floor of the three proglacial gorges and Huiloac gorge were swept away in what was initially a hyperconcentrated flow, but later transformed into a debris flow and then back to a hyperconcentrated flow (Capra *et al.*, 2004). The lahar flowed through Huiloac gorge for 21 km, and passed through the towns located on its perimeter.

On 22 January 2001, a pyroclastic flow crossed the glacier and descended through the three proglacial gorges to a distance of 2 km from the crater. The resulting lahar behaved as a debris flow throughout its course, transporting glacial meltwater and pyroclastic flow materials (Capra *et al.*, 2004). The glacier lost 0.7×10^5 m^3 of liquid water during the massive melting (Andrés *et al.*, 2007). The maximum peak discharge was 667 m^3/s at 4 km from the initial point and the discharge stabilised at <40 m^3/s at 5 km downstream from the previous point (Muñoz-Salinas *et al*., 2007). In addition to the major laharic events, other secondary flows occurred on 2 April 1998, 7 July 1999, 24 May 2000, March 2001 and April 2005 (CENAPRED, 2009). Finally, the volcanic activity resulted in glacier extinction (Julio-Mirnda *et al*. 2008).

Methods

Field analysis

Within this study, three sectors along Huiloac gorge where trees showed obvious signs of the influence of past laharic activity were investigated. The uppermost sector (Sector 1) extends from 3800–3700 m asl, where the predominant tree

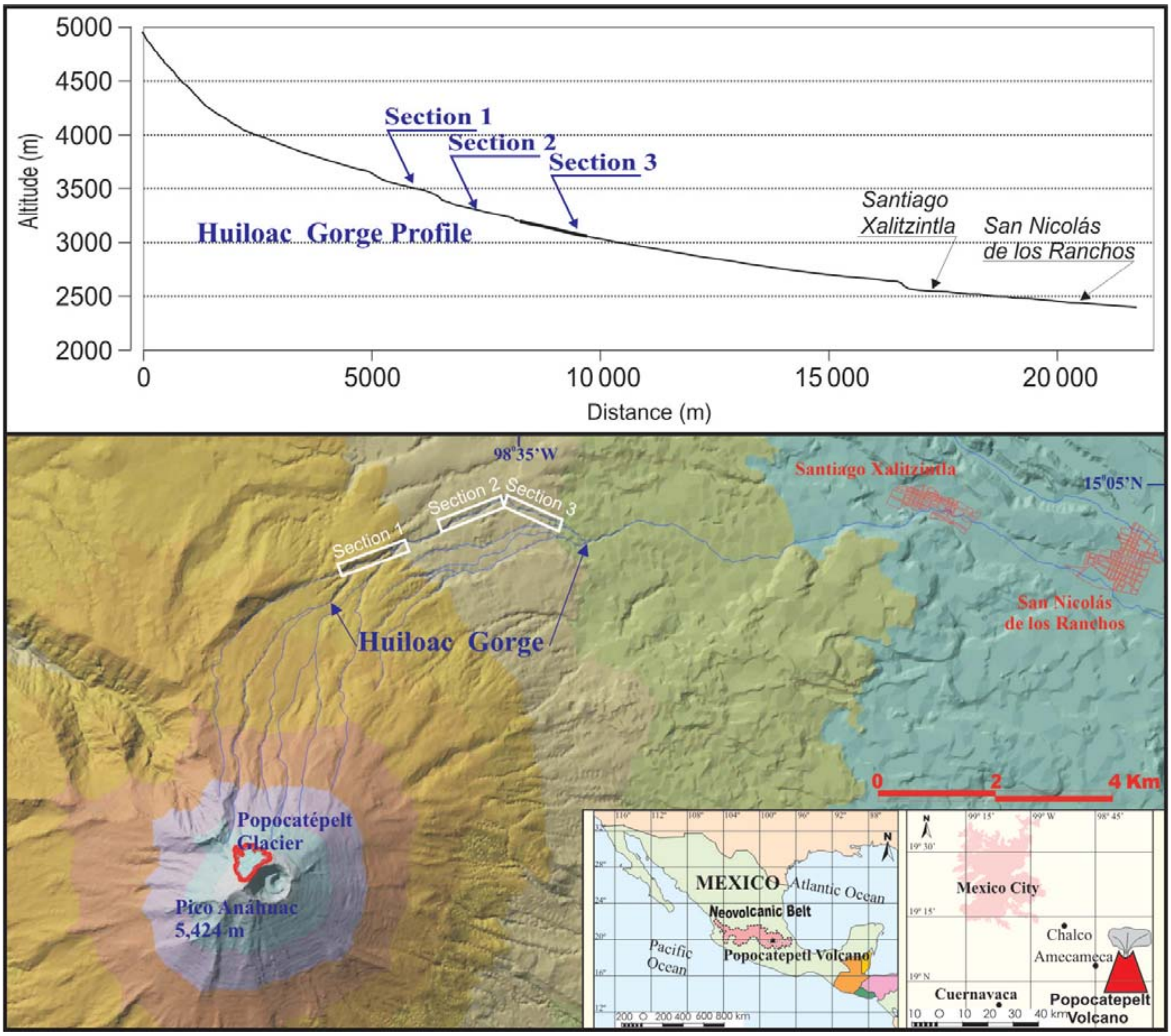

Figure 1 The study area is located on the Northern flank of Popocatépetl volcano in the Mexican Neovolcanic belt. Three sectors have been investigated along the Huiloac gorge at elevations between 3800 and 3150 m asl

species is Mexican Mountain Pine (*Pinus hartwegii* Lindl.). Sector 2 (330 –3250 m asl) and Sector 3 (3250–3150 m asl) are located adjacent to each other farther downslope and the forest cover is mainly composed of Sacred Fir (*Abies religiosa* (H.B.K.) Schlecht. & Cham.) and Mexican White Pine (*Pinus ayacahuite* Ehrenb.).

Figure 2 illustrates the geomorphology of the gorge in the investigated sector and the aspect of trees disturbed by lahar events. In Sector 1 (Figure 2A), the channel cuts through loose volcaniclastic deposits (ash-fall on the surface and lahar underneath) but below 3–4 m, indurated lahar and pyroclastic flow deposits inhibit incision, thus causing a widening of the gorge. In contrast, the gorge is considerably narrower and deeper in Sectors 2 (Figure 2B) and 3 (Figure 2C), where it cuts through a sequence of loose lahar and pryroclastic flow deposits up to ca. 25 m in thickness, locally underlain by a lava flow. The entire pyroclastic sequence cut by the gorge was produced by the eruptive activity of the 9th century AD. In Figure 2D and E trees injured by past lahar events located in the middle and the lower sector are illustrated.

In the three sectors of Huiloac gorge, a total of 62 trees was sampled of which 21 were *A. religiosa,* 22 were *P. hartwegii* and 19 were *P. ayacahuite* (Table 1). Sampled trees were obviously affected by past lahar activity and showed external disturbances such as injuries, burial of stem base, decapitation, inclination of stem or denudation of roots (Figure 3). Trees were selected very carefully and all trees impacted by any influence other than lahars – such as rotational slumps, other small-scale movements or anthropogenic influence – were disregarded. Collections were made of 137 increment cores and 3 cross-sections from these apparently affected trees. Cores were extracted using an increment borer (max. length 40 cm, diameter 6 mm). Two cores per tree were normally extracted, one in the flow direction, one on the opposite side of the trunk. Sampling height was chosen according to the morphology of the stem. Tilted or injured trees were sampled at the height of the disturbance, whereas decapitated trees or trees with a buried stem base were cored as close to the ground as possible to gather a maximum of information. Samples from injured trees were taken at the edge of the wound so as to avoid missing

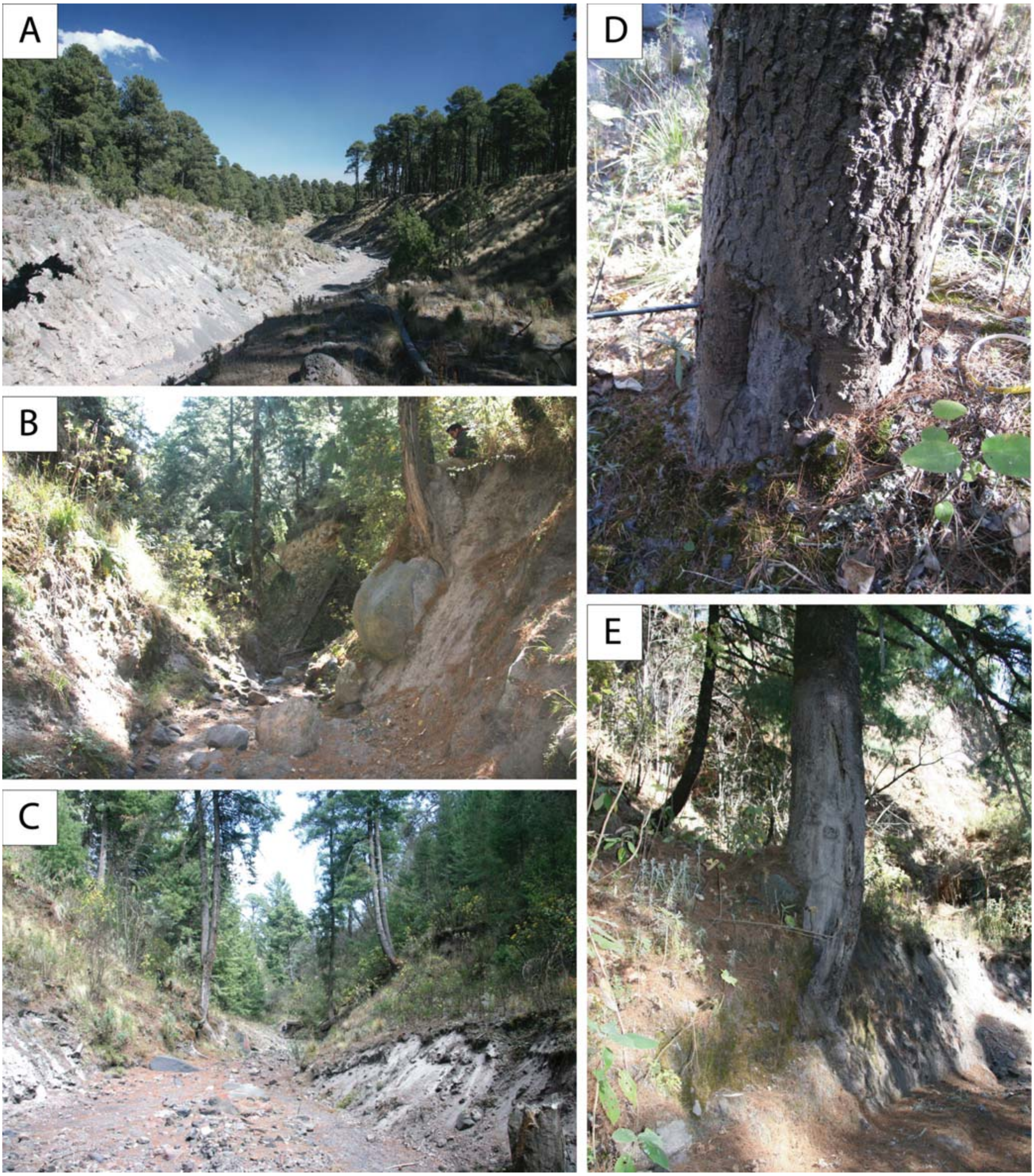

Figure 2 Aspect of the Huiloac gorge in the (A) upper, (B) middle and (C) lower investigated sectors. (D) and (E): injuries of different dimensions attest the passage of past lahars in the gorge

tree rings through abrasion or decomposition (Stoffel and Bollschweiler, 2008, 2009). Small injured trees were sampled with cross-sections using a handsaw.

Information noted for each tree included: (i) tree species; (ii) description of the disturbance and morphology; (iii) vertical and horizontal distance of the tree to the channel; (iv) tree diameter at breast height; (v) position of the cores sampled (i.e. upslope, downslope, other); (vi) information on neighbouring trees; and (vii) information on other possible influences. The trees were then positioned on a sketch map of the sector of the gorge.

Table 1 Number of trees sampled per sector and per tree species

	Sector 1 3800–3700 m asl	Sector 2 3300–3250 m asl	Sector 3 3250–3150 m asl	Total
Abies religiosa	0	14	7	21
Pinus hartwegii	22	0	0	22
Pinus ayacahuite	0	10	9	19
Total	22	24	16	62

Laboratory analysis

In the laboratory, samples were analysed following the standard procedure described in Stoffel and Bollschweiler (2008, 2009). Individual steps included the sanding of increment cores and measurement of tree-ring widths using an LINTAB measuring device and TSAP software (Time Series Analysis and Presentation; Rinntech, 2009). Growth curves of disturbed trees were then cross-dated with a corresponding reference chronology composed of 28 *Pinus montezumae* unaffected by lahars (Victor Peña, pers. comm.), so as to identify missing or faulty tree rings. In addition, this reference chronology helped differentiate climatically driven fluctuations in tree growth from growth disturbances (GD) caused by lahars (Cook and Kairiukstis, 1990; Schweingruber, 1996). The trees unaffected by lahars were sampled on relatively gentle slopes outside (and alongside) the north side of Huiloac gorge, at an elevation of 3200–3400 m asl, i.e. next to Sectors 2 and 3 of our study. All sampled trees (n = 28) are *P. montezumae* and cover the period 1932–2005.

Growth curves of the affected trees were then used to determine the initiation of abrupt growth suppression or release. In the case of tilted stems, both the appearance of compression wood cells as well as the ring-width series were analysed (Braam *et al.*, 1987a,b). Additional anatomical changes such as injuries, callus tissue or tangential rows of traumatic resin ducts were noted (Bollschweiler *et al.*, 2008b). Figure 3 provides an overview on the impact of lahars on tree growth and reactions visible in the tree-ring series.

The age structure of the stand was assessed using the age of the selected trees. Since trees were not cored at the stem base and piths were not always present, the age structure does not reflect inception or germination dates of trees, but provides an approximate image of the age distribution of the trees sampled.

For the known 2001 and 1997 events, all GD were compiled and the position of trees with reactions indicated on a sketch map. Additional events were defined by assessing the growth disturbances in the samples, their position within the lahar deposits as well as the spatial distribution of all trees showing growth disturbances in the same year.

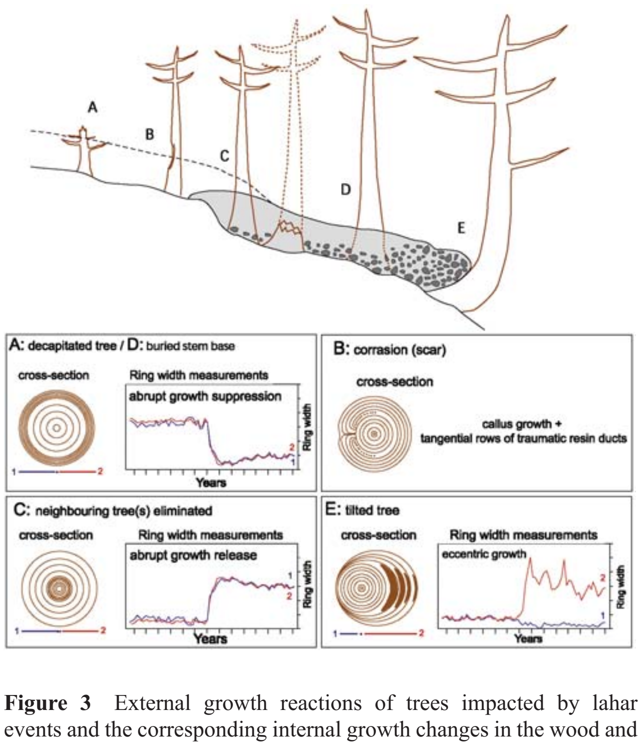

Figure 3 External growth reactions of trees impacted by lahar events and the corresponding internal growth changes in the wood and tree-ring series. Numbers 1 and 2 and corresponding continuous and dashed lines indicate radii of tree stem to either side

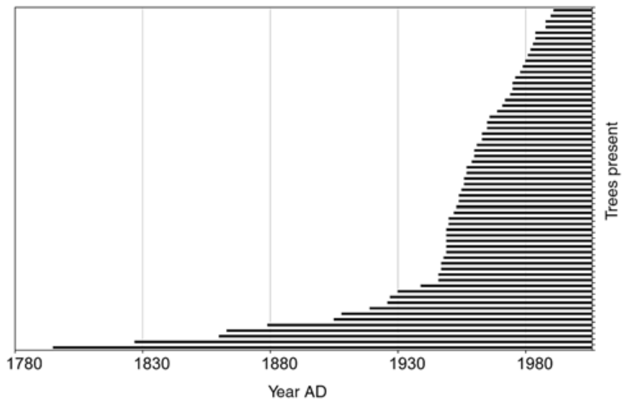

Figure 4 Age structure of the sampled trees at Huiloac gorge. The oldest tree attained sampling height in 1795, whereas the youngest sample reaches back until 1991

Results

Age structure of trees

The mean age of trees in the 3 sectors amounts to 58 years (STDEV: 38 years), with the oldest tree dating back to AD 1795. In contrast, the youngest tree reached sampling height only in AD 1991. While the mean age is similar in Sectors 1 and 3 (50 and 53 years, respectively), trees in Sector 2 reveal a mean age of 70 years. The oldest trees are growing on the uppermost terraces in Sector 2 at a vertical distance of 8–15 m from the current channel bed. Figure 4 provides insights on the overall age structure. Trees older than 100 years were only rarely present in the gorge. In contrast, a period of intense colonisation is observed starting in the mid-1940s, with half of all trees showing innermost rings at sampling height between 1946 and 1969.

Growth disturbances in the tree-ring series

In the 140 samples, a total of 146 growth disturbances (GD) was identified. The most common GD identified in the tree-ring series were abrupt growth suppression (31%) after stem burial, decapitation or denudation of roots. A very common sign of past lahar influence represented injuries (17%) and the adjacent tangential rows of traumatic resin ducts (TRD; 25%). Compression wood as a reaction to stem inclination amounted to 16% of all GD. Finally, abrupt growth release after the elimination of neighbouring trees through an event occurred in 12 cases (8%).

Evidence of the 2001 lahar event

Evidence of the lahar event on 22 January 2001 could be depicted in 18 trees. In Sectors 1 and 3, only little reaction could be found with four and three trees, respectively, showing GD. In Sector 2, in contrast, 11 trees with GD could be identified. The most common GD of trees to the 2001 event were injuries and TRD as well as compression wood. Table 2 provides details on the number and type of reactions per sector.

The position of all trees showing GD after the event was marked on a sketch map so as to give indications on their spatial distribution and the flow height of the event. In Sector 1, the lahar influenced only trees standing on the lowermost terrace at an elevation of ~5 to a maximum of 10 m above the current channel bed. In Sector 2, most trees affected were located close to the channel bed as well, with a mean vertical distance of only 3 m. Trees located at elevations higher than 5 m above the channel bed did not reveal GD. Similarly, trees in Sector 3 were only affected to a maximum

Table 2 Growth disturbances related to the event of 2001 and 1997 (TRD: tangential rows of traumatic resin ducts)

	2001				1997			
	Sector 1	Sector 2	Sector 3	Total	Sector 1	Sector 2	Sector 3	Total
growth suppression	1		1	2	2	6	6	14
TRD		3		3		4		4
injury	1	7	1	9	4		1	5
compression wood	2		1	3	1			1
growth release		1		1	2		2	4
TOTAL	4	11	3	18	9	10	9	28

elevation of 4 m above the channel bed. However, only three trees showed evidence of the 2001 event in this sector. By way of example, the spatial distribution of trees located in Sector 2 and showing GD after the event of 2001 is illustrated in Figure 5.

Evidence of the 1997 lahar event

In 1997, a lahar occurred on 1 July. Evidence for this event could be identified in 28 trees. Affected trees were distributed evenly in the three sectors. The most important GD was abrupt growth suppression found in 14 trees. In addition, 9 trees showed signs of wounding. In contrast, only one tree located in the uppermost sector reacted with the production of compression wood after stem inclination. Table 4 provides details on the type of GD per sector identified in the tree-ring series.

As can be seen in Figure 6, trees affected in Sector 1 are located along a small levee at an elevation of ~8–10 m above the current channel bed. In contrast, trees at higher elevations do not seem to be influenced by the event. In Sector 2, trees positioned in the vicinity of the channel and up to a vertical distance of ~7 m show GD after the event. A similar area of influence can be observed in the lowermost sector, where 9 trees growing at up to 9 m above the channel indicate damage caused by the lahar event.

Reconstruction of previously unknown lahar events

Based on the GD recording the previously known lahar events of 2001 and 1997, the investigation focused on the reconstruction of unknown events. In the tree-ring series of sampled trees, several additional years with further activity could be identified.

In 1983, a total of 13 trees reacted to an event whereof 9 showed signs of wounding and related growth reactions. The spatial position of trees indicates that the impact was more important in the middle and lower sectors with 11 out of the 13 trees being located in this part of the Huiloac gorge. In contrast, in the uppermost sector, only 2 of the 15 trees living at this time showed slight GD from the event.

Another event presumably occurred in 1968/69. Out of the 42 trees present at this time, 9 show evidence of the passage of a flow, mostly in the form of growth suppression. In addition, two injuries represent a strong signal for an event. Again, most trees were located in the lower sectors (2 and 3), with only one tree showing GD in Sector 1.

Even though the relatively small number of three trees showed GD in 1947, this was nevertheless considered a possible lahar event year as only a small number of trees were already present at that moment (16). Furthermore, the intensity of the reactions was strong. TRD, compression wood and growth suppression could be identified in the tree-ring series of trees located in Sectors 1 and 2. In Sector 3, no GD could be identified, as only one tree situated far from the channel was already living at the time of the event.

In 1933, 3 out of 11 trees show signs of lahar activity. One tree reacted to the disturbance with the formation of TRD and two others with distinct growth suppression. All trees are located in Sector 2 on terraces >10 m above the current channel bed.

Another possible event occurred in the period 1919–1921. During this time period, four trees – out of eight living – show GD. Three trees formed TRD and the other one abrupt growth suppression. The spatial position of affected trees indicates the influence of the event on the upper terraces (>10 m above the current channel bed) of Sectors 1 and 2.

Discussion

In this study, we report on results obtained from tree-ring analysis of 140 samples extracted from 62 trees affected by lahar events in the Huiloac gorge, Popocatépetl volcano. Tree age averages 58 years with the oldest tree reaching back to the late 18th century. Tree ages indicated in this study do not refer to germination dates of trees, but rather represent the number of tree rings present at sampling height. The oldest trees are located in the middle sector with four trees reaching back to the 19th century. It seems that their spatial position on the uppermost terraces at 10–15 m above the current channel bed prevented them from being influenced by the more recent lahar activity as they do not reveal GD in the past decades.

An important phase of colonization started in the 1940s with 50% of all trees sampled having their innermost tree ring on the increment cores between AD 1946 and 1969. A possible explanation for this sudden vegetation increase might be a devastating lahar event clearing a pre-existing forest stand in the gorge. In addition, the event may have eventually also led to erosion and therefore incision of the channel, rendering additional surfaces available for the colonisation. In general, a certain time span passes after a clearing event and before new seedlings start colonising the surface. Pierson (2007) refers to this interval as germination lag time (GLT), while previous studies preferred the term "ecesis interval" (Desloges and Ryder, 1990; McCarthy and Luckmann, 1993). According to Pierson (2007), this GLT for surfaces newly formed through lahars varies between 1 and 14 years, depending on the climatic and soil conditions as well as on the availability of seeds. A study on the plant succession after lahar events in Huiloac demonstrated that *Pinus* sp. started recolonising the deposits a few years after the event (Muñoz-Jimenez *et al.*, 2005). In the present study, additional years must be added between the clearing event and the colonisation as tree rings were missing due to the sampling height and the absence of the pith on many samples (Bollschweiler *et al.*, 2008a). Therefore, a possible clearing event would have occurred before about 1940.

In the tree-ring series of affected trees, a total of 146 growth disturbances (GD) could be assessed. Injuries could mainly be identified in relation with the youngest events. An explanation for this fact is that wounds in conifer trees tend to heal their injuries quickly and can therefore no longer be discerned on the stem surface after the complete closure of the wound (Schweingruber, 1996; Stoffel and Perret, 2006). Therefore, older events might be underestimated as overgrown injuries could not be found in the tree-ring series. In most conifer trees, tangential rows of traumatic

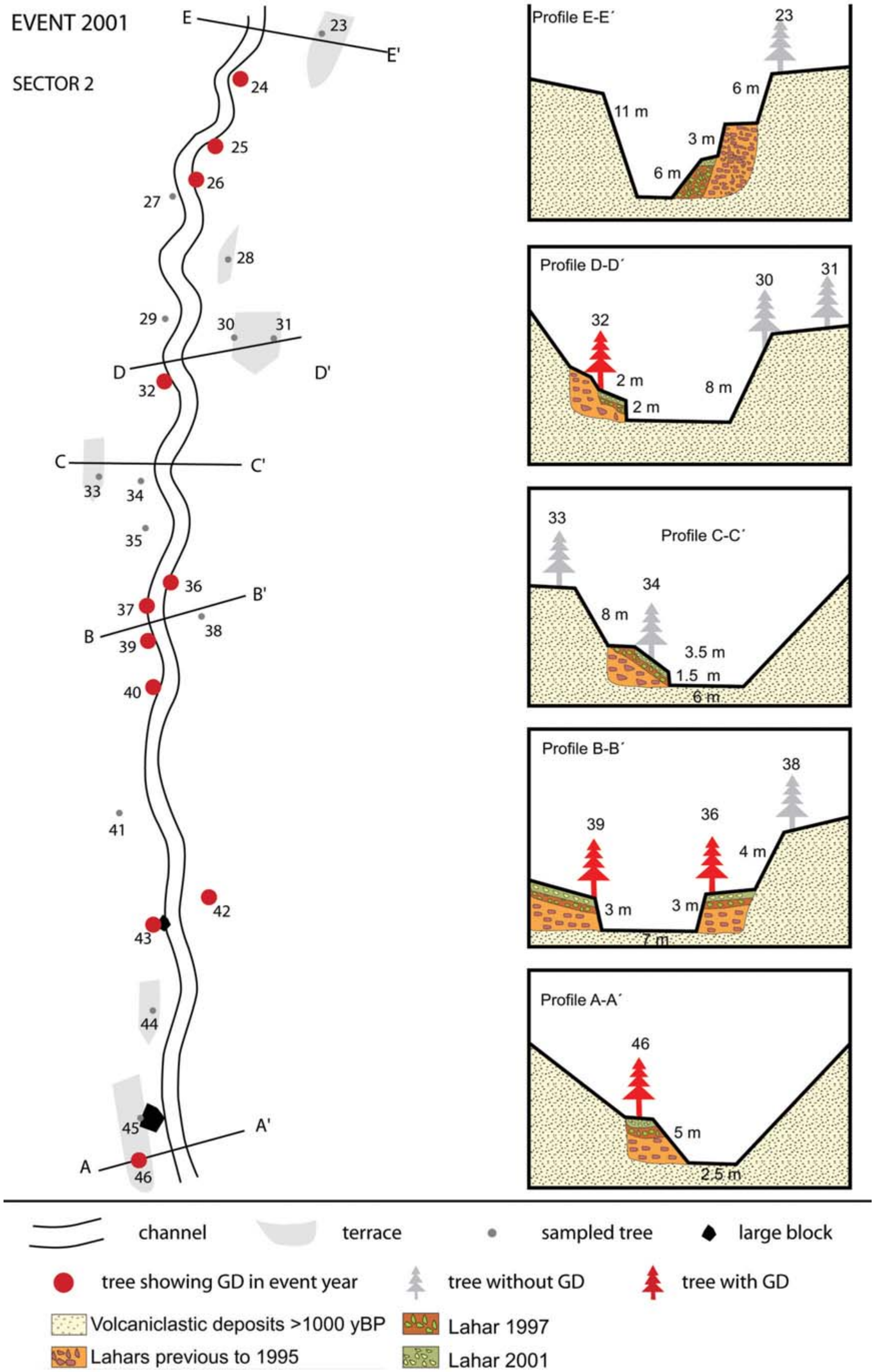

Figure 5 Spatial distribution of trees in Sector 2 showing growth disturbances after the 2001 lahar event

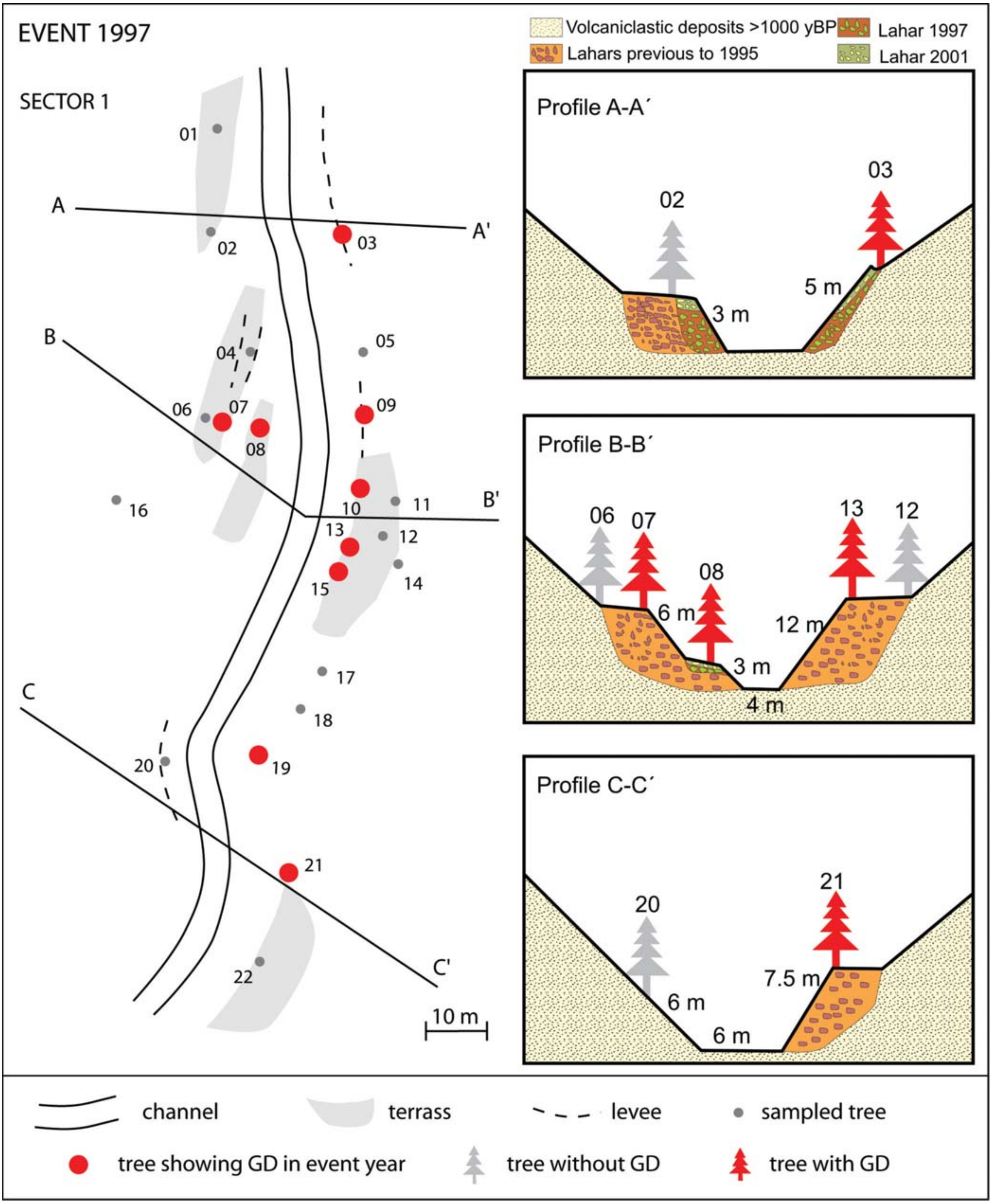

Figure 6 Spatial distribution of trees in Sector 1 showing growth disturbances after the 1997 lahar event

resin ducts (TRD) are formed at the edges of the injury, which allow dating of the event with yearly and sometimes even monthly precision (Stoffel and Beniston, 2006; Schneuwly and Stoffel 2008), even if the increment core has been sampled at a certain distance of the wound. Several TRD could be identified in the *Abies religiosa* trees. *Pinus ayacahuite* and *Pinus hartwegii* do not, in contrast, form TRD – as is common in *Pinus* species (Bannan, 1936) – and this dating tool can therefore not be used. Nevertheless, tree species investigated in this study have proved to be highly suitable for the reconstruction of geomorphic events.

Evidence for the lahar event of 22 January 2001 could be identified abundantly in the growth series of the sampled trees. The passing flow has caused a large number of injuries in the tree stems. The type of growth disturbance seems to be influenced by the texture and granulometry of the flow. Material transported during the 2001 lahar was relatively fine-grained, with clasts generally <70 cm in diameter (Capra *et al.*, 2004). It seems that this composition facilitated the wounding of trees through abrasion of the bark and the subjacent cambium. In contrast, forces were apparently only rarely strong enough to incline tree stems. While the spatial distribution of damaged trees indicates that Sector 2 was especially affected by the 2001 event, only a rather limited number of trees was disturbed in Sectors 1 and 3. Regarding the geomorphology in the sectors, the gorge undergoes a significant narrowing between Sector 1 and 2, which could have led to a change in flow height. Similarly, bulking processes could have occurred in the upper part of the gorge as the channel runs through unconsolidated material in this stretch.

The lahar event of 1 July 1997 was registered in the tree-ring series with a total of 28 GD distributed evenly through the 3 sectors. In contrast to the 2001 event, a large number of trees revealed growth suppression in addition to injuries and TRD. The 1997 event has left much more important deposits of up to 15 m in the gorge (Capra *et al.*, 2004) in comparison to the event of 2001. This depositional process has lead to distinct stem burial and subsequent growth suppression in the tree-ring series.

Earlier debris-flow events in 1983, 1968/69, 1947 and 1933 were represented in the tree-ring series with a smaller number of GD. As there has not been any recorded volcanic activity on Popocatépetl volcano between AD 1928 and 1994 (Palacios, 1996), these events could not have been triggered directly by volcanic eruptions. Therefore, they must represent rainfall-induced rather than volcano-induced lahars. Rainfall-induced lahars occur on volcanic slopes when intense precipitation falls onto abundant loose debris in the form of pyroclastic-flow or -fall deposits (Vallance, 2000). Lahars of this type are commonly small, a factor explaining the limited number of trees displaying signs of these events. However, it is also obvious that small events remaining within the channel bed, without affecting trees on the terraces and slopes, will rarely be detected with dendrogeomorphological methods. Hence, the small-scale events recorded by CENAPRED (2009) during the past decade (1998, 1999, 2000, 2001, 2005) were not identified in the tree-ring series. No older records are available as there are no meteorological or gauging stations in the study area. In addition, small-scale events were not necessarily noticed in the town downstream as they are located ~8 km downstream from the study site. This reconstruction has to be seen as representing the minimum frequency of events. Nevertheless, rainfall-induced lahars seem to have occurred on several occasions during the 20th century and this process must therefore not be neglected in the hazard assessment.

In contrast to the apparently rainfall-triggered lahars in the mid-20th century, the GD dated to the period 1919–1921 might be the results of volcano-induced lahars. As indicated by several authors, Popocatépetl was active in AD 1919 when dynamite explosions from a sulphur mine in the interior of the crater provoked new volcanic activity (Waitz, 1921; Murillo, 1939; Palacios, 1996). This volcanic activity was responsible for a retreat of the glacier snout from 4335 m asl in 1920 to ~4800 m asl in 1921 (White, 1981) and therefore could have caused the release of one or several lahars between 1919 and 1921. However, dating precision based on dendrogeomorphological methods is reduced for this period, as only a very limited number of the trees sampled had ages >80 years.

Conclusion

In this study we report on results obtained from tree-ring series of 62 trees heavily affected by past lahar activity in Huiloac gorge. On the basis of the growth disturbances caused by the known 2001 and 1997 lahar events, five additional and previously unknown events could be identified in the samples for the 20th century. Tree-ring investigations performed on *P. ayacahuite*, *A. religiosa* and *P. hartwegii* demonstrated the potential of Mexican conifer species for dendrogeomorphic reconstructions. As shown in this study, data obtained through tree-ring investigations improved knowledge on previous lahar activity and can therefore be of considerable importance for the assessment of hazards and the prediction of future incidences. This method can be applied to other study sites, in order to reconstruct past lahar events.

Through the investigation of meteorological data, threshold values for the release of lahars can be defined. In order to provide evidence of flow heights or possibly even flow velocities, additional studies with a larger number of samples would be necessary. Detailed geomorphic mapping and high precision mapping of trees in the area could further improve information on the spatial pattern of past events.

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References

Andrés, N., Zamorano, J.J., Sanjosé, J.J., Atkinson, A. and **Palacios, D.** 2007: Glacier retreat during the recent eruptive period of Popocatépetl volcano (Mexico). *Annals of Glaciology* 45, 73–82.

Bannan, M.W. 1936: Vertical resin ducts in the secondary wood of the Abietineae. *New Phytologist* 35, 11–46.

Biondi, F., Galindo Estrada, I., Elizalde Torres, A. and **Gavilanes, J.C.** 2003: Tree growth response to the 1913 eruption of Volcán de Fuego de Colima, Mexico. *Quaternary Research* 59, 293–99.

Bollschweiler, M. and **Stoffel, M.** 2007: Debris flows on forested cones – reconstruction and comparison of frequencies in two catchments in Val Ferret, Switzerland. *Natural Hazards and Earth System Sciences* 7, 207–18.

Bollschweiler, M., Stoffel, M., Ehmisch, M and**, Monbaron, M.** 2007: Reconstructing spatio-temporal patterns of debris-flow activity with dendrogeomorphological methods. *Geomorphology* 87, 337–51.

Bollschweiler, M., Stoffel, M. and **Schneuwly, D.M.** 2008a: Dynamics in debris-flow activity on a forested cone – a case study using different dendroecological approaches. *Catena* 72, 67–78.

Bollschweiler, M., Stoffel, M., Schneuwly, D.M. and **Bourqui, K.** 2008b: Traumatic resin ducts in *Larix decidua* stems impacted by debris flows. *Tree Physiology* 28, 255–63.

Braam, R.R., Weiss, E.E.J. and **Burrough, A.** 1987a: Spatial and temporal analysis of mass movement using dendrochronology. *Catena* 14, 573–584.

—— 1987b: Dendrogeomorphological analysis of mass movement, A technical note on the research method. *Catena* 14, 585–89.

Brantley, S., Yamaguchi, D., Cameron, K. and **Pringle, P.** 1986: Tree-ring dating of volcanic deposits. *Earthquakes and Volcanoes* 18, 184–94.

Briffa, K.R., Jones, P.D., Schweingruber, F.H. and **Osborn, T.J.** 1998: Influences of volcanic eruptions on northern hemisphere summer temperature over the past 600 years. *Nature* 393, 450–57.

Camacho, H. 1925: Apuntes acerca de la actividad del Popocatépetl en relación con la sismología. *Anales del Instituto Geológico* 2, 38–67.

Cameron, K.A. and **Pringle, P.T.** 1986: Post-glacial lahars of the Sandy River basin, Mount Hood, Oregon. *Northwest Science* 60, 225–37.

Capra, L., Poblete, M.A. and **Alvarado, R.** 2004: The 1997 and 2001 lahars of Popocatépetl volcano (Central Mexico), textural and

sedimentological constraints on their origin and hazards. *Journal of Volcanology and Geothermal Research* 131, 351–69.
CENAPRED 2009: Volcanic Monitoring (1994–2009) from the Cenapred Web site: www.cenapred.unam.mx
Cook, E.R. and **Kairiukstis, L.A.** 1990: *Methods of Dendrochronology – Applications in the Environmental Sciences*. Kluwer, London.
Cronin, S.J., Hodgson, K.A., Neall, V.E., Palmer, A.S. and **Lecointre, J.A.** 1997: 1995 Ruapehu lahars in relation to the late Holocene lahars of Whangaehu River, New Zealand. *New Zealand Journal of Geology and Geophysics* 40, 507–20.
Davila, N., Capra, L., Gavilanes-Ruiz, J.C., Varley, N., Norini, G. and **Gómez Vazques, A.** 2007: Recent lahars at Volcán de Colima (Mexico), Drainage variation and spectral classification. *Journal of Volcanology and Geothermal Research* 165, 127–41.
Desloges, J.R. and **Ryder, J.M.** 1990: Neoglacial history of the Coast Mountains near Bella Coola, British Columbia. *Canadian Journal of Earth Sciences* 27, 281–90.
Fisher, R.V. and **Schmincke, H.V.** 1984: *Pyroclastic Rocks*. Springer, Berlin Heidelberg, New York.
Hupp, C.R. 1984: Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California. *Environmental Geology and Water Sciences* 6, 121–28.
Julio-Miranda, P., Delgado-Granados H., Huggel, C. and **Kääb A.** 2008: Impact of the eruptive activity on glacier evolution at Popocatépetl Volcano (México) during 1994–2004. *Journal of Volcanology and Geothermal Research* 170, 86–98.
LaMarche, V.C. and **Hirschboek, K.K.** 1984: Frost rings in trees as records of major volcanic eruptions. *Nature* 307, 121–26.
Macías, J.L. 2005: Geología e historia eruptiva de algunos de los grandes volcanes activos de México. *Boletín de la Sociedad Geológica Mexicana*, LVII, 379–424.
McCarthy, D.P. and **Luckman, B.H.** 1993: Estimating ecesis for tree-ring dating of moraines, a comparative study from the Canadian Cordillera. *Arctic, Antarctic and Alpine Research* 25, 63–68.
Munoz-Jimenez, J., Rangel-Rios, K. and **Garcia-Romero, A.** 2005: Plant Colonization of Recent Lahar Deposits on Popocatepetl Volcano, Mexico. *Physical Geography* 26, 192–215.
Muñoz-Salinas, E., Manea, V.C., Palacios, D. and **Castillo-Rodriguez, M.** 2007: Estimation of lahar flow velocity on Popocatépetl volcano (Mexico). *Geomorphology* 92, 91–99.
Murillo, G. 1939: La actividad del Popocatépetl. In: *Volcanes de México*, Ed. Polis, Mexico, I, 13.
Palacios, D. 1996: Recent geomorphic evolution of a glaciovolcanic active stratovolcano, Popocatépetl (Mexico). *Geomorphology* 16, 319–35.
Palacios, D., Zamorano, J.J. and **Gomez, A.** 2001: The impact of present lahars on the geomorphologic evolution of proglacial gorges, Popocatépetl, Mexico. *Geomorphology* 37, 15–42.
Pierson, T.C. 2007: Dating young geomorphic surfaces using age of colonizing Douglas fir in southwestern Washington and northwestern Orgegon, USA. *Earth Surface Processes and Landforms* 32, 811–31.
Pierson, T.C., Janda, R.J., Thouret, J.-C. and **Borrero, C.A.** 1990: Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *Journal of Volcanology and Geothermal Research* 41, 17–66.
Priester, A. 1927: Notas preliminares sobre vestigios glaciares en el Estado de Hidalgo y en el Valle de Mexico. *Memorias de la Sociedad Cientifica Antonio Alzate* 48, 1–13.
Rinntech 2009: LINTAB – Precision ring by ring: *www.rinntech.com/Products/LINTAG.htm.*
Robin, C. and **Boudal, C.** 1987, A gigantic bezymianny-type event at the beginning of modern volcan Popocatépetl. *Journal of Geology and Geothermal Research* 31, 115–30.
Salzer, M.W. and **Hughes, M.K.** 2007: Bristlecone pine tree rings and volcanic eruptions over the last 5000 yr. *Quaternary Research* 67, 57–68.
Schneuwly, D.M. and **Stoffel, M.** 2008: Tree-ring based reconstruction of the seasonal timing, major events and origin of rockfall on a case-study slope in the Swiss Alps. *Natural Hazards and Earth System Sciences* 8, 203–11.
Schweingruber, F.H. 1996: *Tree Rings and Environment*. Dendroecology. Paul Haupt, Bern, Stuttgart, Wien.
Scott, K.M., Vallance, J., Kerle, N., Macías, J.L., Strauch, W. and **Devoli, G.** 2005: Catastrophic precipitation triggered lahar at Casita volcano, Nicaragua, occurrence, bulking and transformation. *Earth Surface Processes and Landforms* 30, 56–79.
Scuderi, L.A. 1990: Tree-ring evidence for climatically effective volcanic eruptions. *Quaternary Research* 34, 67–85.
Sheppard, P.R., Ort, M.H., Anderson, K.C., Elson, M.D., Vázquez-Selem, L., Clemens, A.W., Little, N.C. and **Speakman, R.J.** 2008: Multiple dendrochronological signals indicate the eruption of Parícutin volcano, Michoacán, Mexico. *Tree Ring Research* 64, 97–108.
Siebe, C., Abrams, M., Macías, J.L. and **Obenholzner, J.** 1996: Repeated volcanic disasters in Prehispanic time at Popocatépetl, Central México: Past key to the future? *Geology* 24, 399–402.
Smith, G.A. and **Fritz, W.J.** 1989: Volcanic influences on terrestrial sedimentation. *Geology* 17, 375–76.
Solomina, O., Pavlova, I., Curtis, A., Jacoby, G., Ponomareva, V. and **Pevzner M.** 2008: Constraining recent Shiveluch volcano eruptions (Kamchatka, Russia) by means of dendrochronology. *Natural Hazards and Earth System Sciences* 8, 1083–97.
Stoffel, M. and **Beniston, M.** 2006: On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate, a case study from the Swiss Alps. *Geophysical Research Letters* 33, L16404.
Stoffel, M. and **Bollschweiler, M.** 2008: Tree-ring analysis in natural hazards research – an overview. *Natural Hazards and Earth System Sciences* 8, 187–202.
—— 2009: What tree rings can tell about earth-surface processes. Teaching the principles of dendrogeomorphology. *Geography Compass* 3, 1013–37.
Stoffel, M. and **Perret, S.** 2006: Reconstructing past rockfall activity with tree rings, some methodological considerations. *Dendrochronologia* 24, 1–15.
Stoffel, M., Schneuwly, E., Bollschweiler, M., Lièvre, I., Delaloye, R., Myint, M. and **Monbaron, M.** 2005: Analyzing rockfall activity (1600–2002) in a protection forest – a case study using dendrogeomorphology. *Geomorphology* 68, 224–41.
Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I. and **Maître, G.** 2008: Unraveling the patterns of late Holocene debris-flow activity on a cone in the central Swiss Alps, chronology, environment and implications for the future. *Global and Planetary Change* 60, 222–34.
Strunk, H. 1989: Dendrogeomorphology of debris flows. *Dendrochronologia* 7, 15–25.
—— 1991: Frequency distribution of debris flow in the Alps since the "Little Ice Age". *Zeitschrift für Geomorphologie N.F.,* Supplement 83, 71–81.
—— 1997: Dating of geomorphological processes using dendrogeomorphological methods. *Catena* 31, 137–51.
Thouret, J.C. and **Lavigne, F.** 2000: Lahars, occurrence, deposit and behaviour of volcano-hydrologic flows. In Leyrit, H. and Montenat, C., editors, *Volcaniclastic rocks from magmas to sediments.* Gordon and Breach Science Publishers, Amsterdam, pp. 51–74.
Vallance, J.W. 2000: Lahars. In Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H. and Stix, J., editors, *Encyclopedia of Volcanoes*. Academic Press, San Diego, 602–15.
Waitz, P. 1921: La nueva actividad y el estado actual del Popocatépetl. *Memorias de la Sociedad Cientifica Antonio Alzate* 37, 295–313.
Ward, H.G. 1985: *México en 1927.* SEP, Mexico.
White, S.E. 1981: Neoglacial to recent glacial fluctuations on the volcano Popocatépetl, Mexico. *Journal of Glaciology* 27, 356–63.
Yamaguchi, D.K. and **Hoblitt, R.P.** 1995: Tree-ring dating of pre-1980 volcanic flowage deposits at Mount St. Helens, Washington. *GSA Bulletin* 107, 1077–93.
Yamaguchi, D.K., Hoblitt, R.P. and **Lawrence, D.B.** 1990: A new tree-ring date for the "floating island" lava flow, Mount St. Helens, Washington. *Bulletin of Volcanology* 52, 545–50.